

Testing predictions for central exclusive processes in the early LHC runs¹

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Abstract

We show that the early LHC measurements can provide crucial checks of the different components of the formalism used to predict the cross sections of central exclusive processes.

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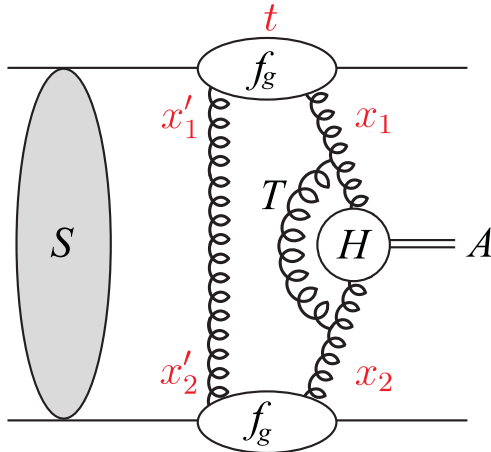


Figure 1: A symbolic diagram for the central exclusive production of a system A .

1 Introduction

The benefits of using forward proton detectors as a tool to study Standard Model (SM) and New Physics at the LHC have been fully appreciated only recently, see for instance, [1] - [4]. The measurements of central exclusive production (CEP) is a prime target of the FP420 project [5], which aims at the installation of forward detectors in the LHC tunnel 420 m from the interaction points of the ATLAS and CMS experiments. The combined detection of both outgoing protons and the centrally produced system gives access to a rich programme of studies in QCD, electroweak, Higgs and BSM physics. Importantly, these measurements will provide valuable information on the Higgs sector of MSSM and other popular BSM scenarios, see [6] - [9]. In particular, the CEP process allows for the unique possibility to study directly the coupling of Higgs-like bosons to bottom quarks [1, 10].

The theoretical formalism [11] - [13] for the description of a CEP process contains quite distinct parts, shown symbolically in Fig. 1. We first have to calculate the $gg \rightarrow A$ subprocess, H , convoluted with the gluon distributions f_g . Next we must account for the QCD corrections which reflect the absence of additional QCD radiation in the hard subprocess – that is, for the Sudakov factor T . Finally, we must enter soft physics to calculate the survival probability S^2 of the rapidity gaps.

The uncertainties of the CEP predictions are potentially not small. Therefore, it is important to perform checks using processes that will be accessible in the first runs of the LHC [14] with integrated luminosities in the range 100 pb^{-1} to 1 fb^{-1} . In [14] we identified reactions where the different ingredients of the formalism used to calculate CEP could be tested experimentally. We first consider measurements which do not rely on proton tagging and can be performed through the detection of rapidity gaps.

The main uncertainties of the CEP predictions are associated with

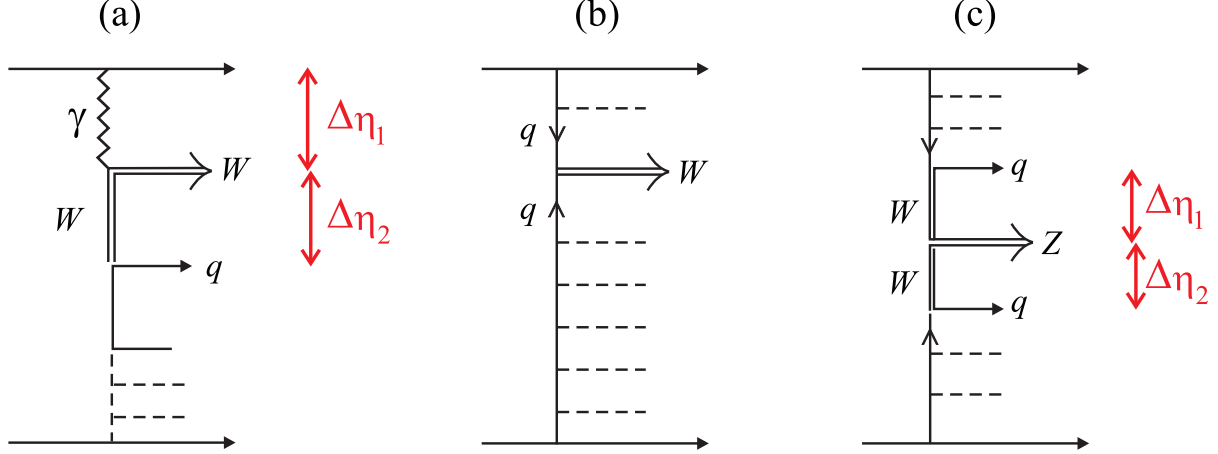


Figure 2: Diagrams for (a) W production with 2 rapidity gaps, (b) inclusive W production, and (c) Z production with 2 rapidity gaps.

- (i) the probability S^2 that additional secondaries will not populate the gaps;
- (ii) the probability to find the appropriate gluons, that are given by generalized, unintegrated distributions $f_g(x, x', Q_t^2)$;
- (iii) the higher order QCD corrections to the hard subprocess, where the most important is the Sudakov suppression;
- (iv) the so-called semi-enhanced absorptive corrections (see [15, 16]) and other effects, which may violate the soft-hard factorization.

2 Gap survival probability S^2

As a rule, the gap survival probability is calculated within a multichannel eikonal approach [17]. The probability S^2 of elastic pp rescattering, shown symbolically by S in Fig. 1 can be evaluated in a model independent way once the elastic cross section $d\sigma_{\text{el}}/dt$ is measured at the LHC. However, there may be some excited states between the blob S and the amplitude on the right-hand-side of Fig. 1. The presence of such states enlarges the absorptive correction. In order to experimentally check the role of this effect, we need to consider a process with a bare cross section that can be reliably calculated. Good candidates are the production of W or Z bosons with rapidity gaps. In the case of ‘ W +gaps’ production the main contribution comes from the diagram shown in Fig. 2(a) [18]. One gap, $\Delta\eta_1$, is associated with photon exchange, while the other, $\Delta\eta_2$, is associated with the W . The cross section is proportional to the quark distribution at a large scale and not too small x , where the uncertainties of the parton densities are small. To select these events in the early LHC runs, we can use the rapidity gap trigger combined with a high p_t lepton or jet trigger.

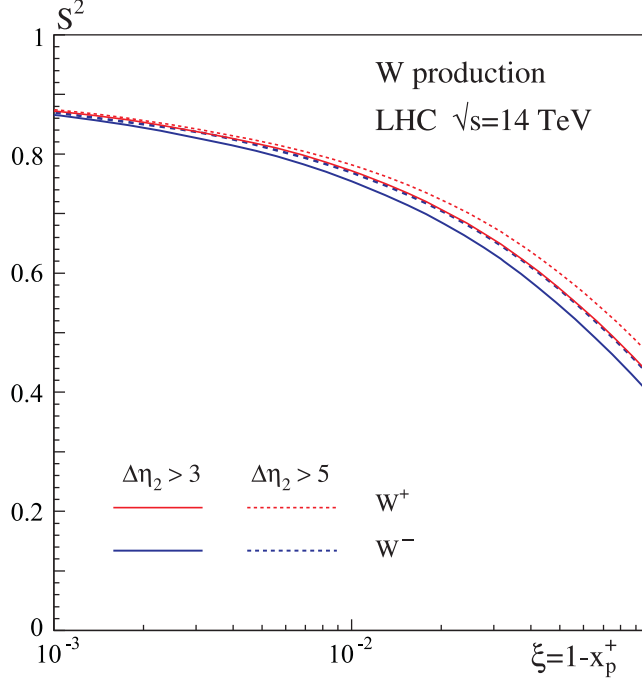


Figure 3: The rapidity gap survival factor S^2 as a function of ξ calculated using the global soft model of [12], assuming that the valence (sea) quarks are associated with the weak (strong) absorptive components. The small spread of the predictions arising from the different partonic content of the diffractive eigenstates means that W +gaps events offer a meaningful test of the S^2 factor.

An important point here is that the minimum value of $|t|$ of the photon, $|t_{\min}| \simeq \frac{m_N^2 \xi^2}{1-\xi}$, is not negligible. Note that the momentum fraction $x_p = 1 - \xi$ associated with the upper proton can be measured by summing the momentum fractions of the outgoing W and the hadrons observed in the calorimeters. As illustrated in Fig. 3 the rescattering reduces the cross section by the factor S^2 . The curves in Fig. 3 were calculated within the scenario where the valence quark is allocated to the component with the smallest absorption and the sea quark to the absorptive component with largest cross section. Since the valence quark contribution is more important for W^+ production and for the configuration with the largest gap size $\Delta\eta_2$, the expected gap survival factor S^2 is found to be larger. In the first LHC data runs the ratio (W +gaps/ W inclusive) will be measured first. This measurement is a useful check of the models for soft rescattering.

A good way to study the low impact parameter (b_t) region is to observe Z boson production via WW fusion, see Fig. 2(c). Here, both of the rapidity gaps originate from heavy boson exchange, and the corresponding b_t region is similar to that for exclusive Higgs production. The expected Z +gaps cross section is of the order of 0.2 pb, and $S^2=0.3$ for $\Delta\eta_{1,2} > 3$ and for quark jets with $E_T > 50$ GeV [19].

One problem is that even with the $E_T > 50$ GeV cut, the QCD background arising from

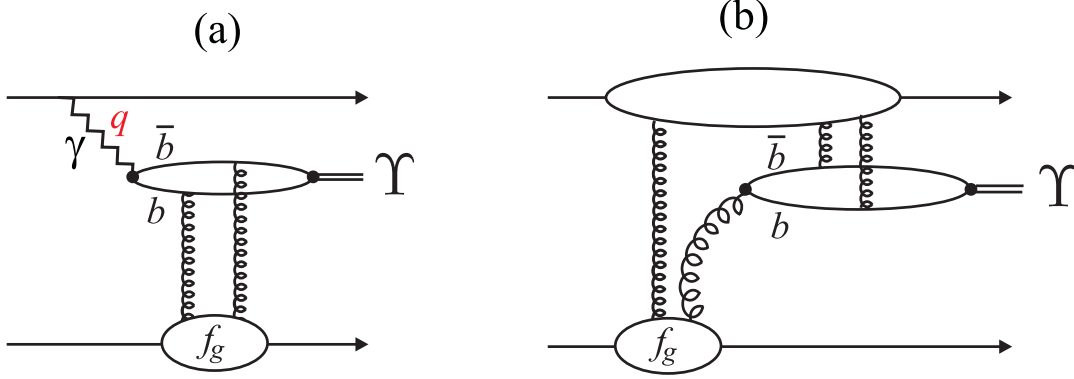


Figure 4: Exclusive Υ production via (a) photon exchange, and (b) via odderon exchange.

QCD $b\bar{b}$ central exclusive production is comparable to the electroweak $q\bar{q} \rightarrow Z + 2 \text{ jet}$ signal. Therefore, we should concentrate on the leptonic decay modes of the Z boson, which results in a smaller event rate ².

When the forward proton detectors become operational we can do more. Both the longitudinal and transverse momentum of the protons can be measured, and we can study the k_t behaviour of the cross section sections and scan the proton opacity [18].

3 Generalized, unintegrated gluon distribution f_g

The cross section for the CEP of a system A essentially has the form [11]

$$\sigma(pp \rightarrow p + A + p) \simeq \frac{S^2}{b^2} \left| \frac{\pi}{8} \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x'_1, Q_t^2, \mu^2) f_g(x_2, x'_2, Q_t^2, \mu^2) \right|^2 \hat{\sigma}(gg \rightarrow A). \quad (1)$$

Here the factor $1/b^2$ arises from the integration over the proton transverse momentum. Also, f_g denotes the generalized unintegrated gluon distribution in the limit of $p_t \rightarrow 0$. The distribution f_g has not yet been measured explicitly. However, in our case it can be obtained from the conventional diagonal gluon distribution, g , known from the global parton analyses, see [11, 14] for details. The main uncertainty here comes from the lack of knowledge of the integrated gluon distribution $g(x, Q_t^2)$ at low x and small scales. For example, taking $Q_t^2 = 4 \text{ GeV}^2$ we find that a variety of recent MRST [21] and CTEQ [22] global analyses give a spread of $xg = (3 - 3.8)$ for $x = 10^{-2}$ and $xg = (3.4 - 4.5)$ for $x = 10^{-3}$. These are big uncertainties bearing in mind that the CEP cross section depends on $(xg)^4$.

To reduce the uncertainty associated with f_g we can measure exclusive Υ production ³. The process is shown in Fig. 4(a). The cross section for $\gamma p \rightarrow \Upsilon p$ [23] is given in terms of exactly the same unintegrated gluon distribution f_g that occurs in Fig. 1.

²Note that in the recent study [20] it was demonstrated that the so-called Track Counting Veto (TCV) is robust for selection of the central rapidity gap events in vector-boson fusion searches at CMS.

³ A feasibility study of the $\gamma p \rightarrow \Upsilon p$ measurement performed by CMS [25] looks quite encouraging.

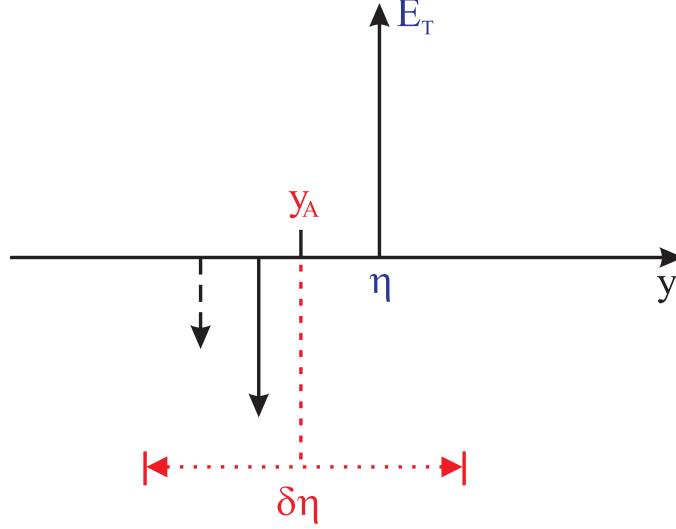


Figure 5: The rapidities of the three jets in the central system. Note that the rapidity y_A of the whole central system does not necessarily occur at $y = 0$. The rapidity interval containing the three jets is denoted by $\delta\eta$, outside of which there is no hadronic activity.

There may be competition between production via photon exchange, Fig. 4(a), and via odderon exchange, see Fig. 4(b). To date, odderon exchange has not been observed. On the other hand, a lowest-order calculation indicates that the odderon process (b) may be comparable to the photon-initiated process (a) (for example, [24]). If the upper proton is tagged, it will be straightforward to separate the two mechanisms since odderon production has no $1/q^2$ singularity characteristic of the photon.

The expression for $\sigma(\gamma p \rightarrow \Upsilon p) \propto f_g^2$ is given in [23]. In order to use this process to constrain the gluon distribution it would be preferable to tag the lower proton.

4 Three-jet events as a probe of the Sudakov factor

Traditionally, the search for the exclusive dijet signal at the Tevatron, $p\bar{p} \rightarrow p + jj + \bar{p}$, is performed [26] by plotting the cross section in terms of the variable $R_{jj} = M_{jj}/M_A$, where M_A is the mass of the whole central system. The R_{jj} distribution is strongly smeared out by QCD bremsstrahlung, hadronization, the jet searching algorithm and other experimental effects [26, 27]. To weaken the role of smearing it was proposed in Ref. [27] to study the dijet distribution in terms of a new variable

$$R_j = 2E_T (\cosh \eta^*)/M_A, \quad (2)$$

where only the transverse energy and the rapidity η of the jet with the *largest* E_T are used in the numerator. Here $\eta^* = \eta - y_A$ where y_A is the rapidity of the whole central system. Clearly

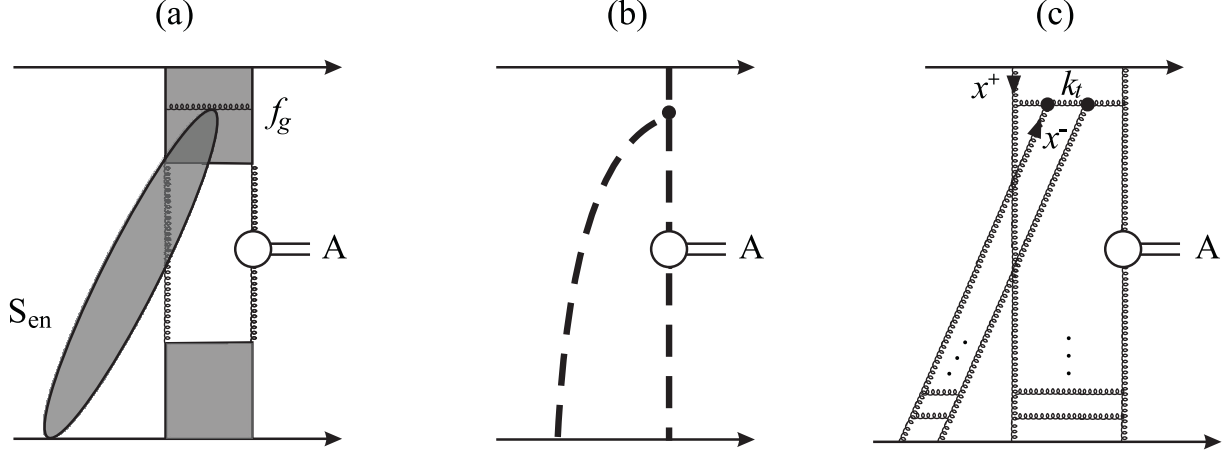


Figure 6: (a) A typical enhanced diagram, where the shaded boxes symbolically denote f_g , and the soft rescattering is on an intermediate parton, giving rise to a gap survival factor S_{en} ; (b) and (c) are the Reggeon and QCD representations, respectively.

the jet with the largest E_T is less affected by hadronization, final parton radiation etc. At leading order, it is sufficient to consider the emission of a third jet, as shown in Fig. 5, where we take all three jets to lie in a specified rapidity interval $\delta\eta$.

The cross section $d\sigma/dR_j$, as a function of R_j , for the exclusive production of a pair of high E_T dijets accompanied by a third jet was calculated and discussed in [27, 14]. It was shown that the measurements of the exclusive two- and three-jet cross sections *as a function of E_T* of the highest jet allow a detailed check of the Sudakov physics; with much more information coming from the observation of the $\delta\eta$ dependence.

A clear way to observe the effect of the Sudakov suppression is just to study the E_T dependence of exclusive dijet production. On dimensional grounds we would expect $d\sigma/dE_T^2 \propto 1/E_T^4$. This behaviour is modified by the anomalous dimension of the gluon and by a stronger Sudakov suppression with increasing E_T . Already the existing CDF dijet data [26] exclude predictions which omit the Sudakov effect.

5 Soft-hard factorization: enhanced absorptive effects

The soft-hard factorization implied by Fig. 1 could be violated by the so-called enhanced Reggeon diagrams, caused by the rescattering of an intermediate parton generated in the evolution of f_g . Such a diagram is shown in Fig. 6(a).

The contribution of the first Pomeron loop diagram, Fig. 6(b) was calculated in pQCD in Ref. [16]. A typical diagram is shown in Fig. 6(c). For LHC energies it was found that the probability of such rescattering may be numerically large. The reason is that the gluon density

grows in the low x region and, for low k_t partons, approaches the saturation limit. However, as shown in [14], the enhanced diagram should affect mainly the very beginning of the QCD evolution – the region that cannot be described perturbatively and which, in the calculations of [12, 13], is already included phenomenologically.

Experimentally, we can study the role of semi-enhanced absorption by measuring the ratio R of diffractive events for W (or Υ or dijet) production as compared to the inclusive process [14]. That is

$$R = \frac{\text{no. of } (A + \text{gap}) \text{ events}}{\text{no. of (inclusive } A) \text{ events}} = \frac{a^{\text{diff}}(x_P, \beta, \mu^2)}{a^{\text{incl}}(x = \beta x_P, \mu^2)} \langle S^2 S_{\text{en}}^2 \rangle_{\text{over } b_t}, \quad (3)$$

where a^{incl} and a^{diff} are the parton densities determined from the global analyses of inclusive and diffractive DIS data, respectively. For W or $\mu^+\mu^-$ production the parton densities a are quark distributions, whereas for dijet or Υ they are mainly gluon densities.

Experimentally, we can observe a double distribution $d^2\sigma^{\text{diff}}/dx_P dy_A$, and form the ratio R using the inclusive cross section, $d\sigma^{\text{incl}}/dy_A$. If we neglect the enhanced absorption, it is quite straightforward to calculate the ratio R of (3). The results for a dijet case are shown by the dashed curves in Fig. 7 as a function of the rapidity y_A of the dijet system. The enhanced rescattering reduce the ratios and lead to steeper y_A distributions, as illustrated by the continuous curves. Perhaps the most informative probe of S_{en}^2 is to observe the ratio R for dijet production in the region $E_T \sim 15 - 30$ GeV. For example, for $E_T \sim 15$ GeV we predict $S_{\text{en}}^2 \sim 0.25, 0.4$ and 0.8 at $y_A = -2, 0$ and 2 respectively.

6 Conclusion

The addition of forward proton detectors to LHC experiments will add unique capabilities to the existing LHC experimental programme. For certain BSM scenarios, the tagged-proton mode may even be the Higgs discovery channel. There is also a rich QCD, electroweak, and more exotic physics, menu.

The uncertainties in the prediction of the rate of a CEP process are potentially not small. Therefore, it is crucial to perform checks of the theoretical formalism using processes that will be experimentally accessible in the first runs of the LHC [14].

Most of the diffractive measurements described above can be performed, without detecting the forward protons, by taking advantage of the relatively low luminosity in the early LHC data runs. This allows the use of a veto trigger to select events with a large rapidity gap(s). In this way we are able to probe the various individual components of the formalism used to predict the CEP cross sections.

To summarise, the gap survival factor, S^2 , caused by eikonal rescattering, may be studied as illustrated in Fig 3 and the possible enhanced, S_{en}^2 , contributions as shown in Figs. 6 and 7.

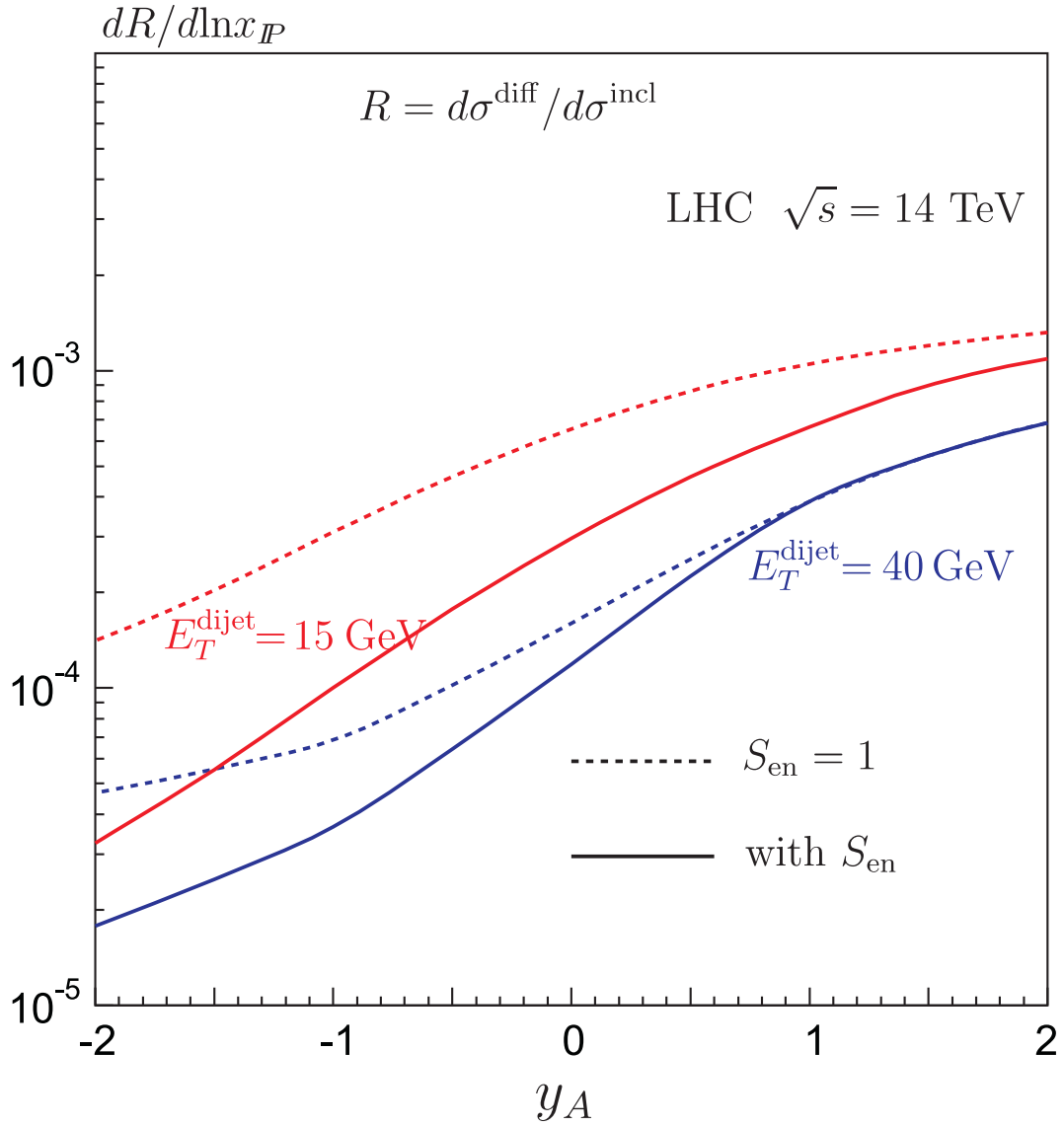


Figure 7: The predictions of the ratio R of (3) for the production of a pair of high E_T jets with (continuous curves) and without (dashed curves) enhanced soft rescattering on intermediate partons.

The relevant unintegrated gluon distribution, f_g , can be constrained by observing Υ production, see Fig. 4, and the QCD radiative effect, T , may be checked by observing exclusive two- and three-jet events.

When the forward proton detectors are operating much more can be done. First, it is possible to measure directly the cross section $d^2\sigma_{\text{SD}}/dtdM_X^2$ for single diffractive dissociation and also the cross section $d^2\sigma_{\text{DPE}}/dy_1dy_2$ for soft central diffractive production. These measurements will strongly constrain the models used to describe diffractive processes and the effects of soft rescattering. The recent predictions can be found in [13]. Next, a study of the transverse momentum distributions of both of the tagged protons, and the correlations between their momenta, is able to scan the proton optical density [18, 28].

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